

Simulation of VSPT Experimental Cascade under High and Low Free-Stream Turbulence Conditions

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Motivation

- A key goal of NASA's **Rotary Wing (RW)** project is to **enhance use of civil rotorcraft to relieve airport congestion and increase capacity.**
- A concept advocated is use of **tilt rotor aircraft** for vertical takeoff and landing.
- For fuel efficiency, the main-rotor speed needs to vary from 100% at takeoff to 55% at cruise.
- To avoid the added weight and complexity of transmission a **variable speed power turbine (VSPT)** can be used with a fixed gear ratio transmission.
- Such variations in the shaft speed of the VSPT lead to a wide range of incidence.



Conditions of VSPT

- Flow in the power turbine is characterized by:
 - Low Reynolds number $< 100,000$ (Re_{Cx2})
 - High turbulence intensity $> (6\%)$
 - Unsteadiness- Multi-Stage
 - Large excursions from optimal incidence > 60 degrees
- Analysis tools are needed to handle physics of the VSPT.
- *A need for models capable of predicting transition and responding to separation has been identified.*

Our Earlier Work

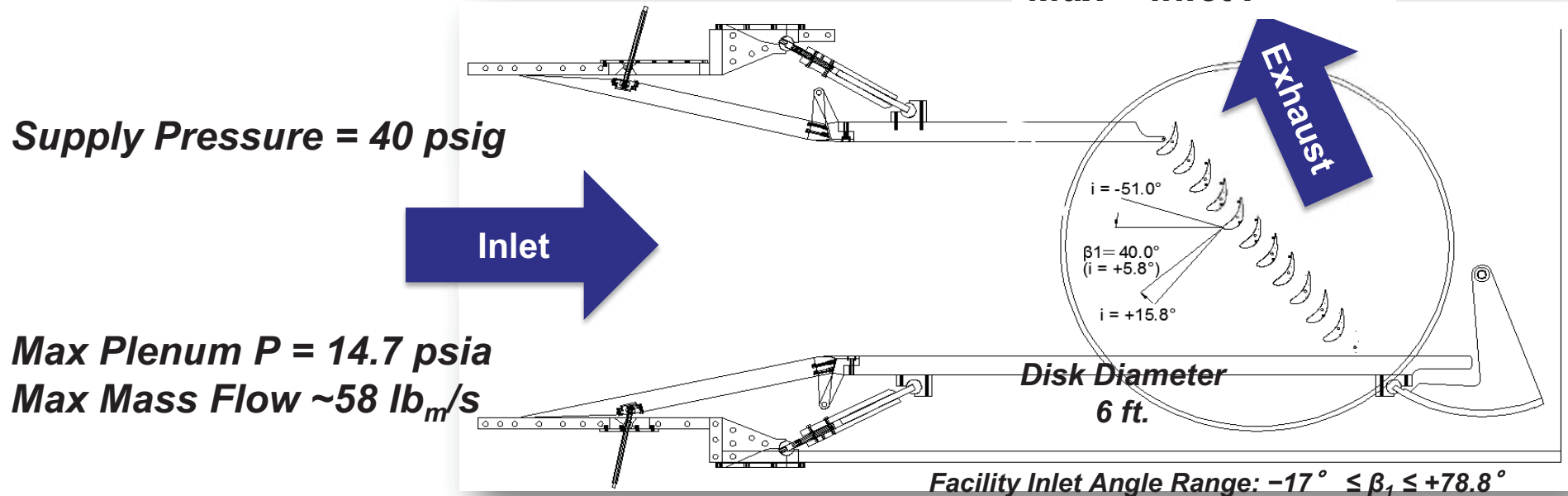
- **Selected and implemented** transition/ turbulence model in our codes.
- **Validated** using *available three-dimensional blade heat transfer data at high turbulence levels, indicating transition.*
- Specifically, “GE2” blade data from earlier work of Giel et al. (GT2003-38839)

Present Work

- NASA has developed notional VSPT blade-set through previous study contract with Rolls-Royce.
- NASA has documented blade performance over **wide incidence angle range** at mission-relevant Reynolds numbers and Mach numbers.
- We need **To Validate** CFD tools for effect of incidence using NASA data from the notional blade.

Transonic Cascade (CW-22)

Exhaust Pressure:
Min $P \approx 2$ psia
Max = inlet P

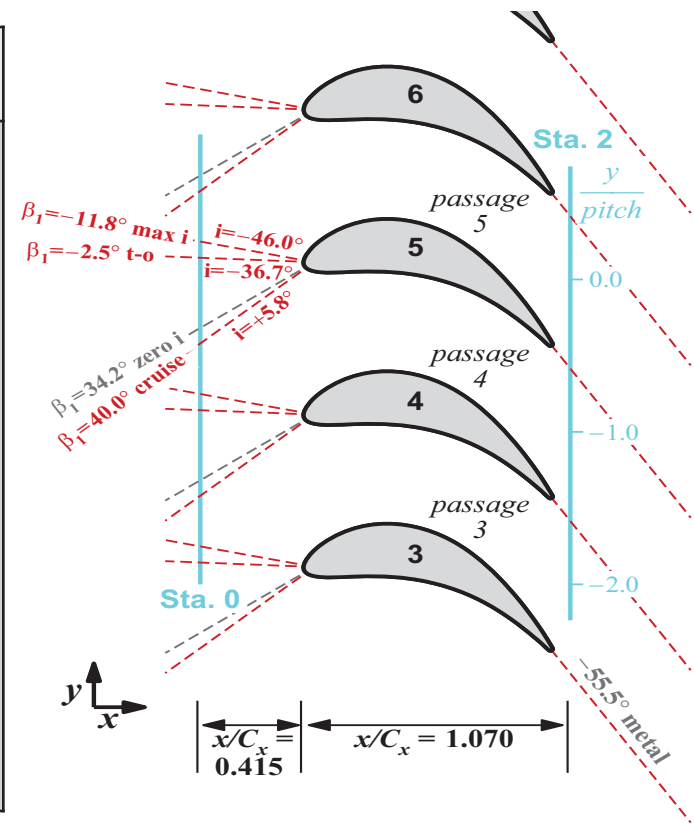


- Data were obtained in NASA-GRC's Transonic Turbine Blade Cascade CW-22
- Large-scale, continuous running facility capable of wide range: Re, M, Tu with adjustable inlet angle.
- Blade/Tip/Endwall aero and heat transfer measurements.

Test Blade

Midspan section of VSPT second stage rotor:
Dimensions and measurement stations.

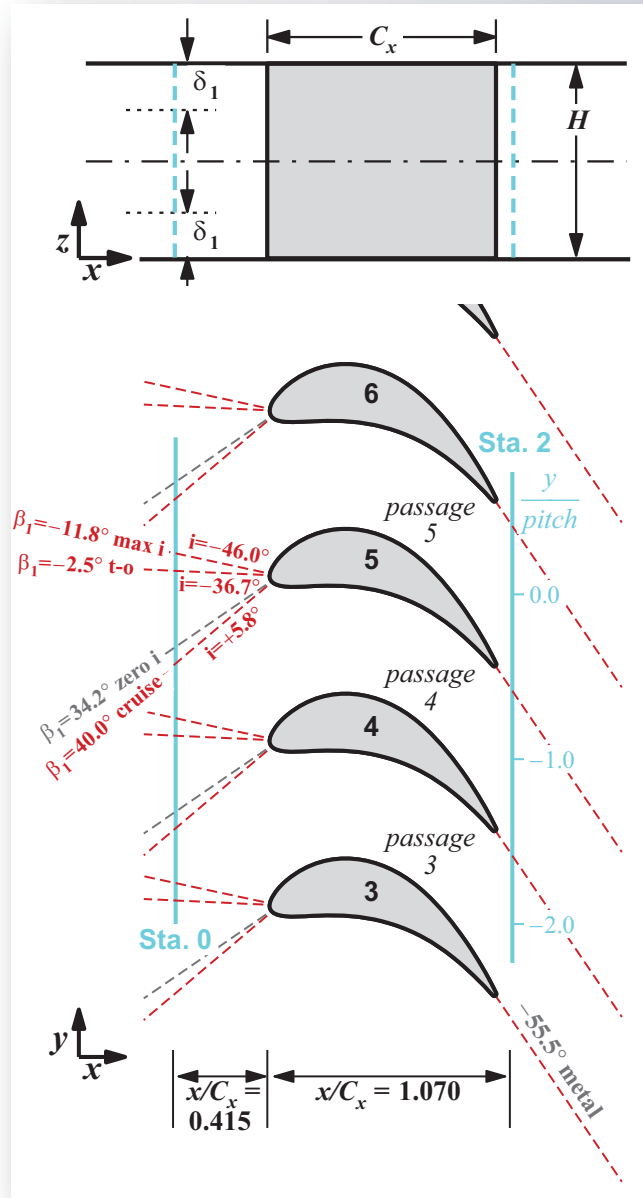
| Geometry | Value, mm (in) |
|--------------------|--------------------|
| Axial Chord, C_x | 180.57 mm (7.109") |
| True Chord | 194.44 mm (7.655") |
| Pitch, S | 130.00 mm (5.119") |
| Span, H | 152.40 mm (6.000") |
| Throat Diameter | 72.85 mm (2.868") |
| Leading Edge Dia. | 15.16 mm (0.597") |
| Trailing Edge Dia. | 3.30 mm (0.130") |
| Stagger Angle | 20.35° |
| Inlet Metal Angle | 34.2° |
| Uncovered Turning | 19.47° |
| Exit Metal Angle | -55.54° |



Experimental Cases for Num. Validation

- A wide Range of variables at various *Reynolds numbers*, *Mach numbers* and *incidence angles* and two *turbulence levels* were measured. (Full data was presented **earlier in this session**)
- Two cases representing ***cruise*** and ***take off*** were documented in detail and are used for this exercise.
- **3d** Blade surface pressure, wake total pressure and blade exit angle distributions were measured.

Test Configuration



- VSPT midspan section blade, $\beta_{1,des} = 34.2^\circ$
- Ten incidence angles: $+15.8^\circ$ to -51.0°
- 5 flow conditions each
- Inlet δ range: 1.16 – 1.69 inches for Low Tu
- Inlet δ range: 0.58 – 0.86 inches for High Tu
- Free-Stream Turbulence, Two conditions:
 - One with no turbulence grid installed
 - One with “blown grid” upstream ($Tu = 0.24\% - 12.0\%$)

Inlet Flow Angles

| Inlet Angle, β_1 | Incidence Angle, i | Z_w |
|--|---------------------------------|-------------|
| 50.0° | 15.8° | 1.22 |
| 45.0° | 10.8° | 1.13 |
| 40.0° (Cruise) | 5.8° | 1.06 |
| 34.2° | 0.0° | 0.99 |
| 28.0° | -6.2° | 0.92 |
| 18.1° | -16.1° | 0.82 |
| 8.2° | -26.0° | 0.74 |
| -2.5° (Takeoff) | -36.7° | 0.65 |
| -11.8° (Mission Max- i) | -46.0° | 0.58 |
| -16.8° | -51.0° | 0.53 |

Choice of Transition Model (Our Earlier Work)

- Surveyed the literature for suitable models.
- Eliminated models which use integral parameters (non-local) such as δ , Θ or any parameter that requires surveying the boundary layer profiles which would limit applicability to 3d flows.
- Identified k_L - k - ω models of Walters and Leylek as candidates (3 equation model.)
- Chose this model based on:
 - Ease and generality of use
 - Recommendations in the literature
 - Tests with transitional heat transfer blade surface data

Application to VSPT

- At low turbulence, WL model results were surprising! Did not agree with data.
- Identified improved k_L - k - ω model of Walters and Cokljat (3 equation model.)
- Results to compare with WL model at high and low turbulence models.

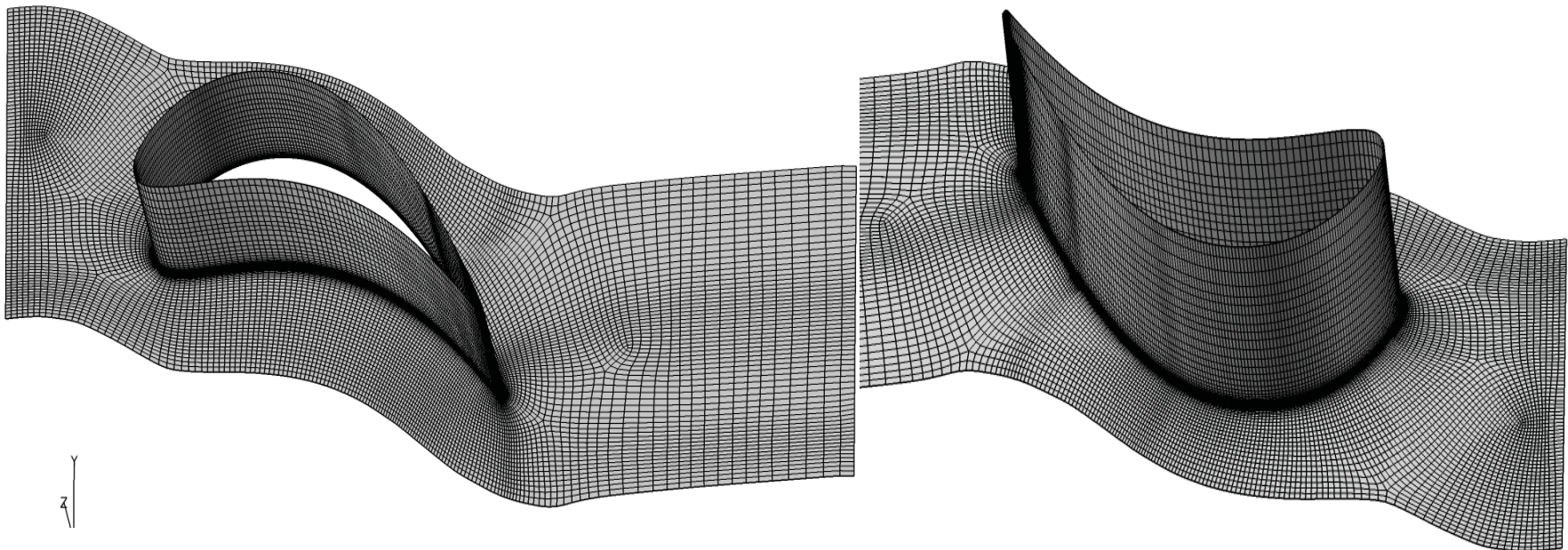
CFD Tool, Glenn-HT

- Full compressible Reynolds-Averaged Navier-Stokes Formulation and Conjugate Heat Transfer
- Multi-block structured grids
- Finite Volume formulation
- Second order central differencing, 4th order artificial dissipation with eigenvalue scaling or,
- Second order upwind schemes, Hunyh, AUSM
- Multi-stage explicit Runge-Kutta time integration with local time stepping
- Multi-grid convergence acceleration
- Dual-Time-Stepping for unsteady simulations
- Parallel processing via MPI

3-D Grids

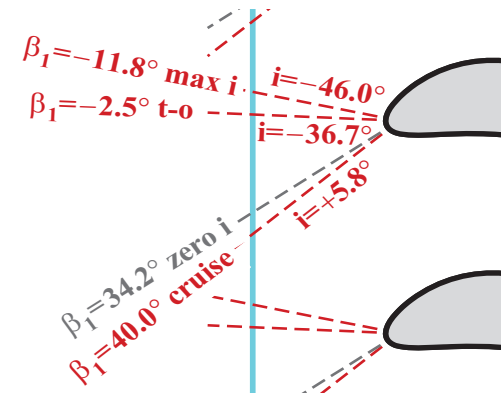
For this work a fine grid was generated (half-span):

- Grid $\sim 7 \times 10^6$ nodes and a stretching ratio of 1.1 away from the walls with $y^+ < 1$
- A coarse grid was also used for startup and for ensuring grid convergence by coarsening Grid by a factor of 2 in each index direction.



Cruise Condition

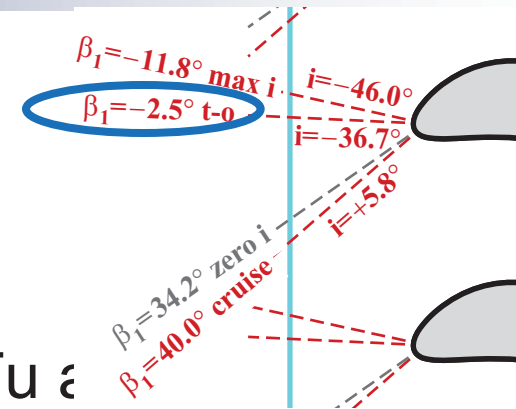
- Blade is operated at $i = +5.8^\circ$ as would occur due to slowing down of rotation
- Reynolds number = 5.4×10^5
- $Tu_{in} = 0.3\%, 12.0\%$
- Turbulence length scale
 - computed from matching Tu at the two stations.
- δ_{in} at the end walls = 25% Span at Low Tu , leads to highly 3d flow. At high Tu 12.0% Span



| Inlet Angle β_1 | Exit Re_{Cx} | Press. Ratio | Exit M_{Is} | δ_{inlet} [inch] | $Tu_{in}\%$ at $-1.5 C_x$ | $Tu_{in}\%$ at $-0.5 C_x$ |
|--------------------------|-------------------|-----------------|------------------|----------------------------|---------------------------------|---------------------------------|
| 40.0° | 536,000 | 1.412 | 0.72 | 1.44 | 0.4 | 0.3 |
| 40.0° | 536,000 | 1.412 | 0.72 | 0.7 | 19 | 12 |

Takeoff Conditions

- Blade incidence is $i = -36.7^\circ$
- Nominal Reynolds number = 5.3×10^5 .
- $Tu = 0.3\%$, **8.5%**
- δ_{in} at the endwalls = 25% span at Low Tu & 12% span at high Tu .
- Turbulence length computed from matching Tu at the two stations.



| Inlet Angle β_1 | Nominal Exit Re_{cx} | Press. Ratio | Exit M_{ls} | δ_{inlet} [inch] | $Tu_{in} \%$ at $-1.5 C_x$ | $Tu_{in} \%$ at $-0.5 C_x$ |
|--------------------------|---------------------------|--------------|------------------|----------------------------|----------------------------------|----------------------------------|
| -2.5° | 532,000 | 1.348 | 0.67 | 1.50 | 0.4* | 0.3* |
| -2.5° | 532,000 | 1.348 | 0.67 | 0.75 | 15.0 | 8.5 |

Turbulence Length Scale

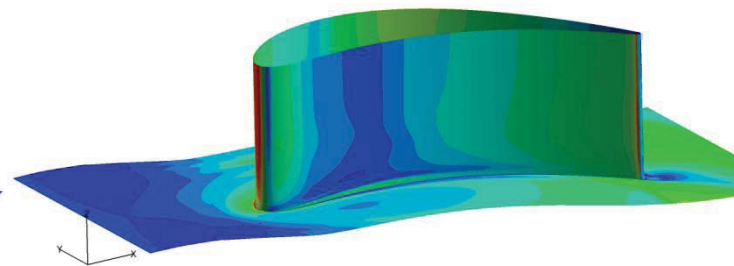
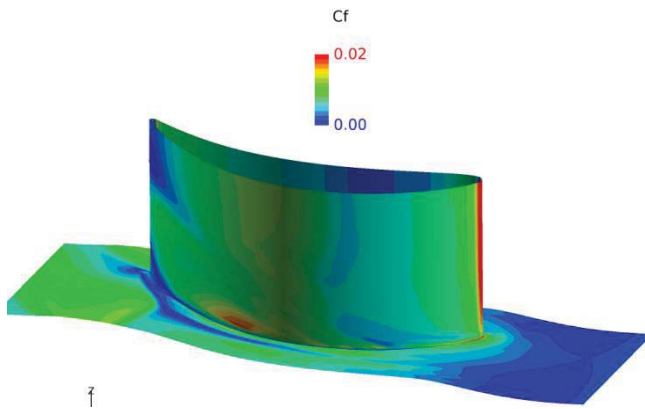
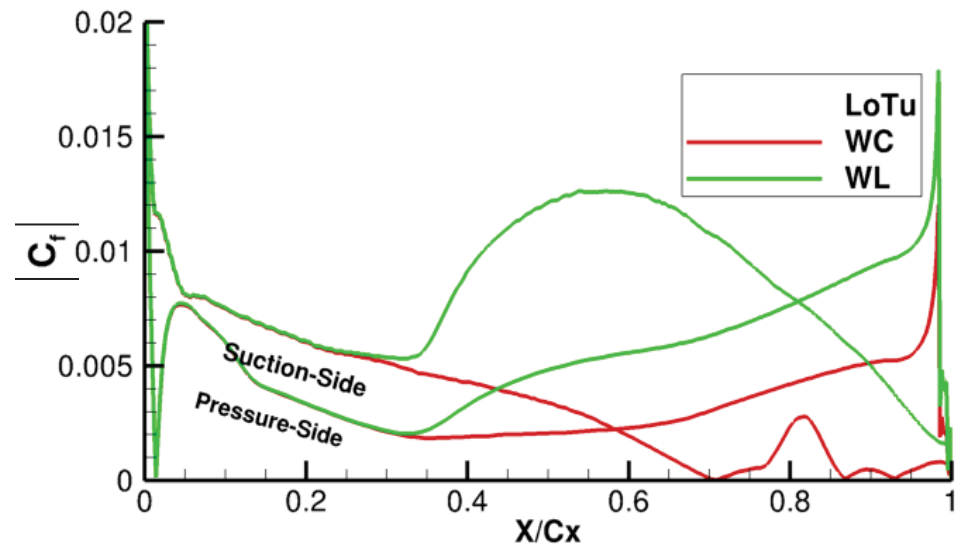
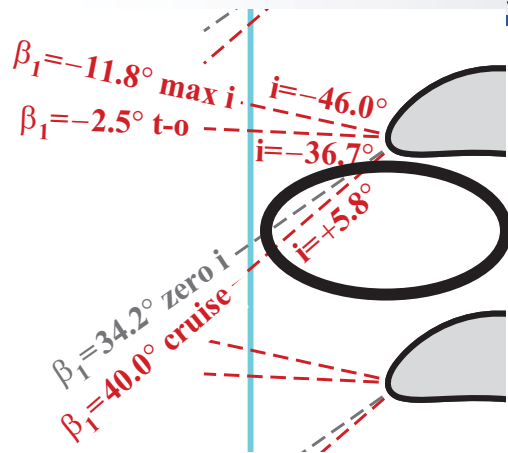
In general:

- Turbulence length scale is input at the inflow boundary.
- Value is usually guessed based on heuristic arguments,
-- examples include, size of turbulence generator bar, span of the passage or the hydraulic diameter of the passage, ...
- In this case Tu was measured at $X = -1.50 \cdot Cx$ and at $-0.5 \cdot Cx$.
- By matching the decay of turbulence, length scale was computed at the inlet to the computational domain at $-0.5 \cdot Cx$.

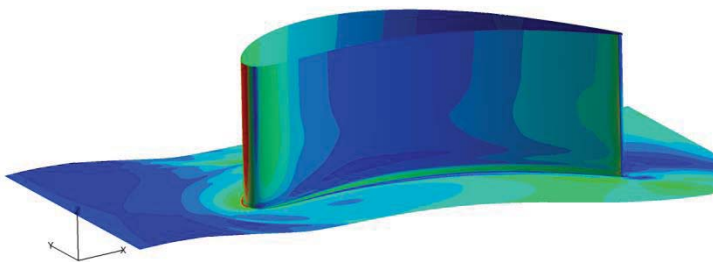
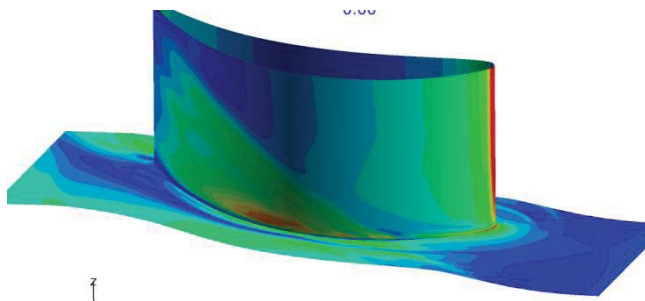
Turbulence Length Scale- Issues

- Issues arise when FST (12%) is present and the decay is to be matched using large values of length scale.
- The problem arises due to excessive entropy generation in the flow at high turbulence intensities.
- For one of the conditions, length scale was dialled down to avoid this excessive loss while the transition location held steady.
- Experiments (Mahallati et al.) suggest that at higher FST the effect of length scale is negligible on transition.
- However, this is still an open issue and needs to be resolved but can be handled.

Transition, Cruise, Low Tu

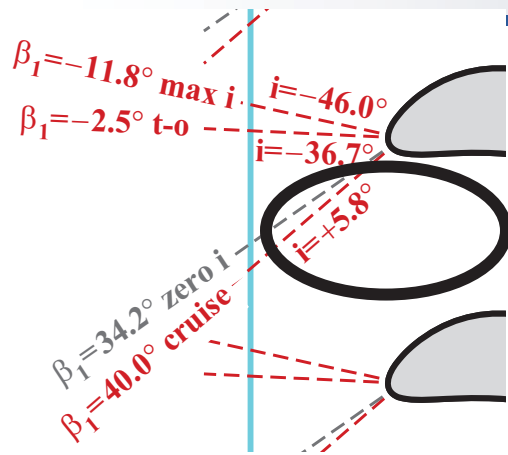


WL

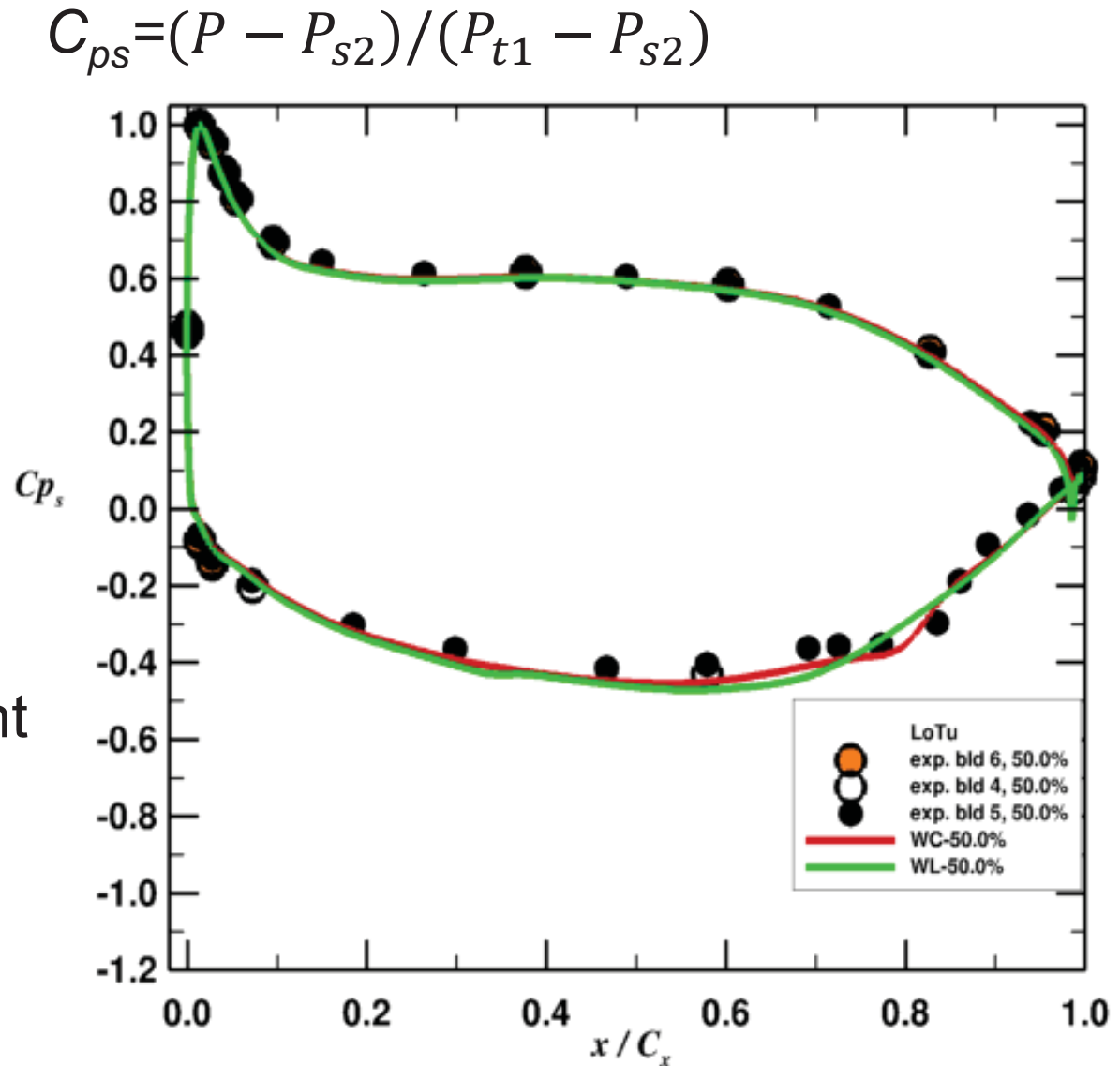


WC

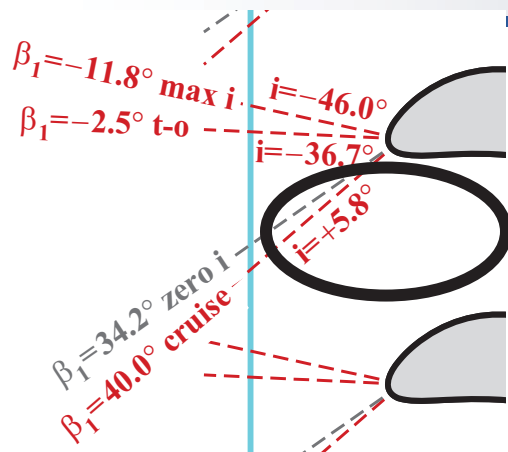
Pressure Distribution- Cruise, Low Tu



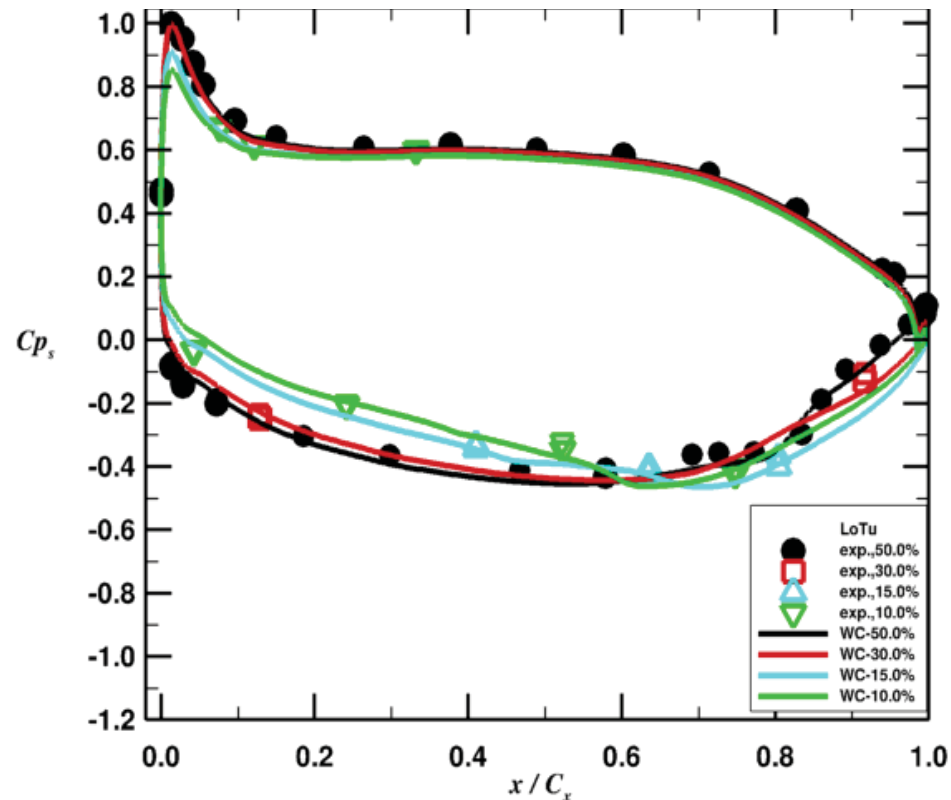
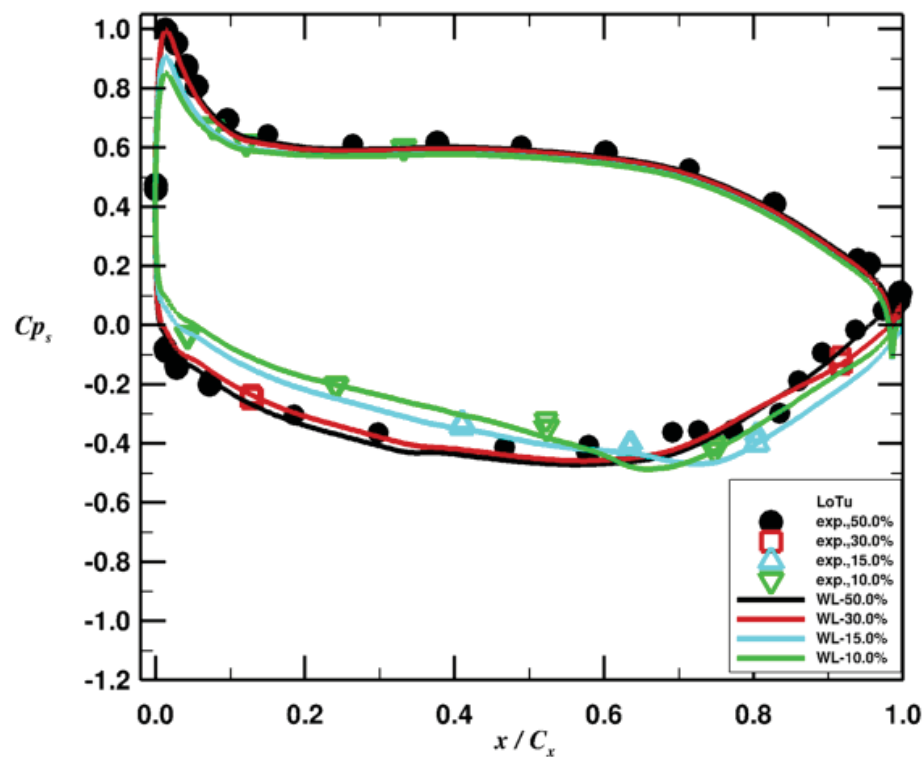
Mid-Span Static
Pressure Coefficient



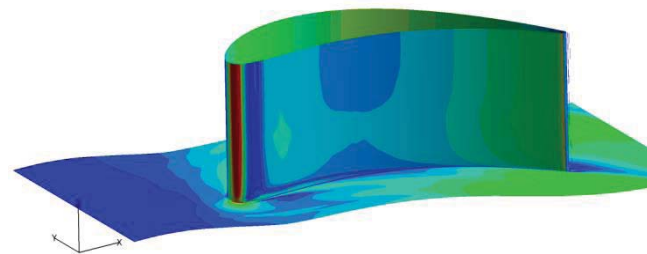
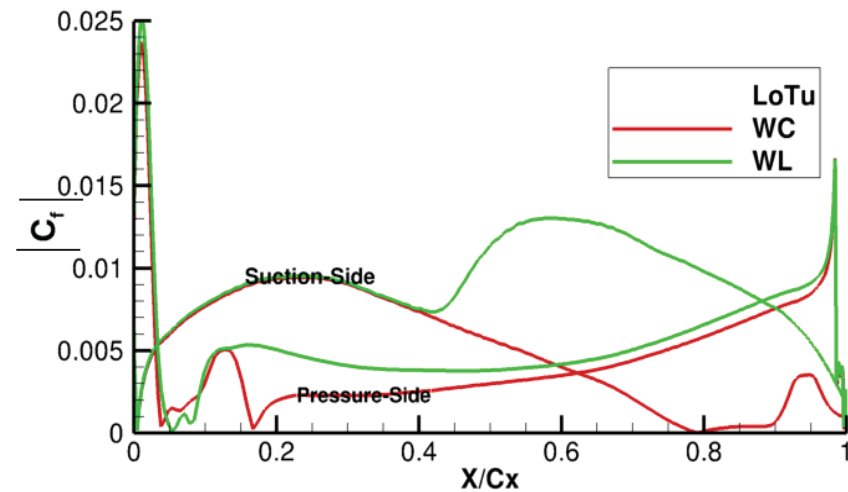
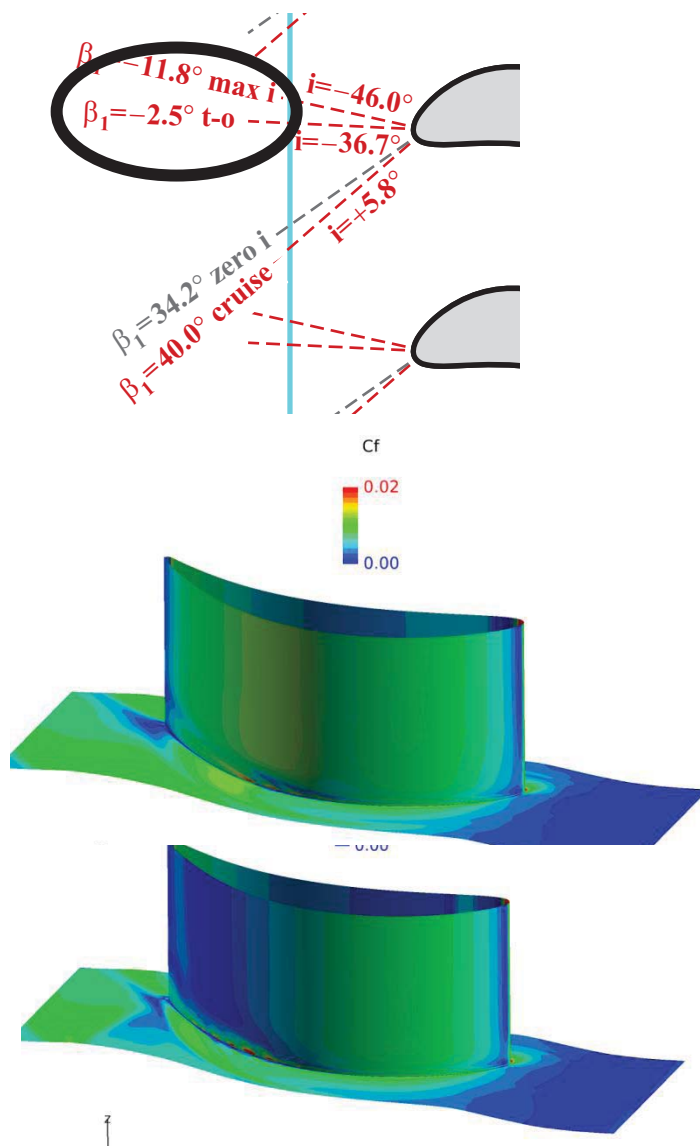
Pressure Distribution- Cruise, Low Tu



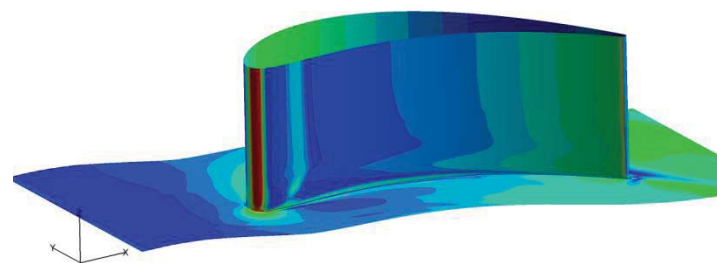
$$C_{ps} = (P - P_{s2}) / (P_{t1} - P_{s2})$$



Transition Takeoff, Low Tu

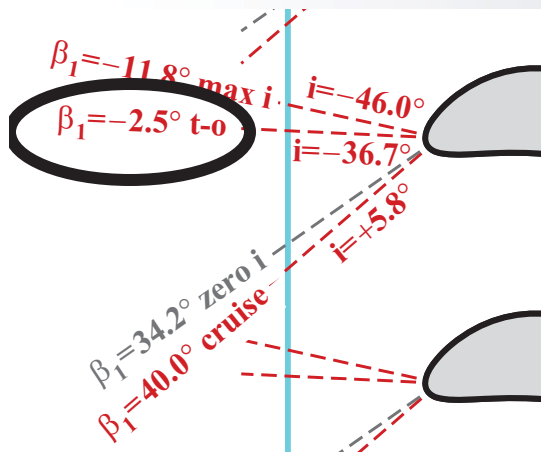


WL

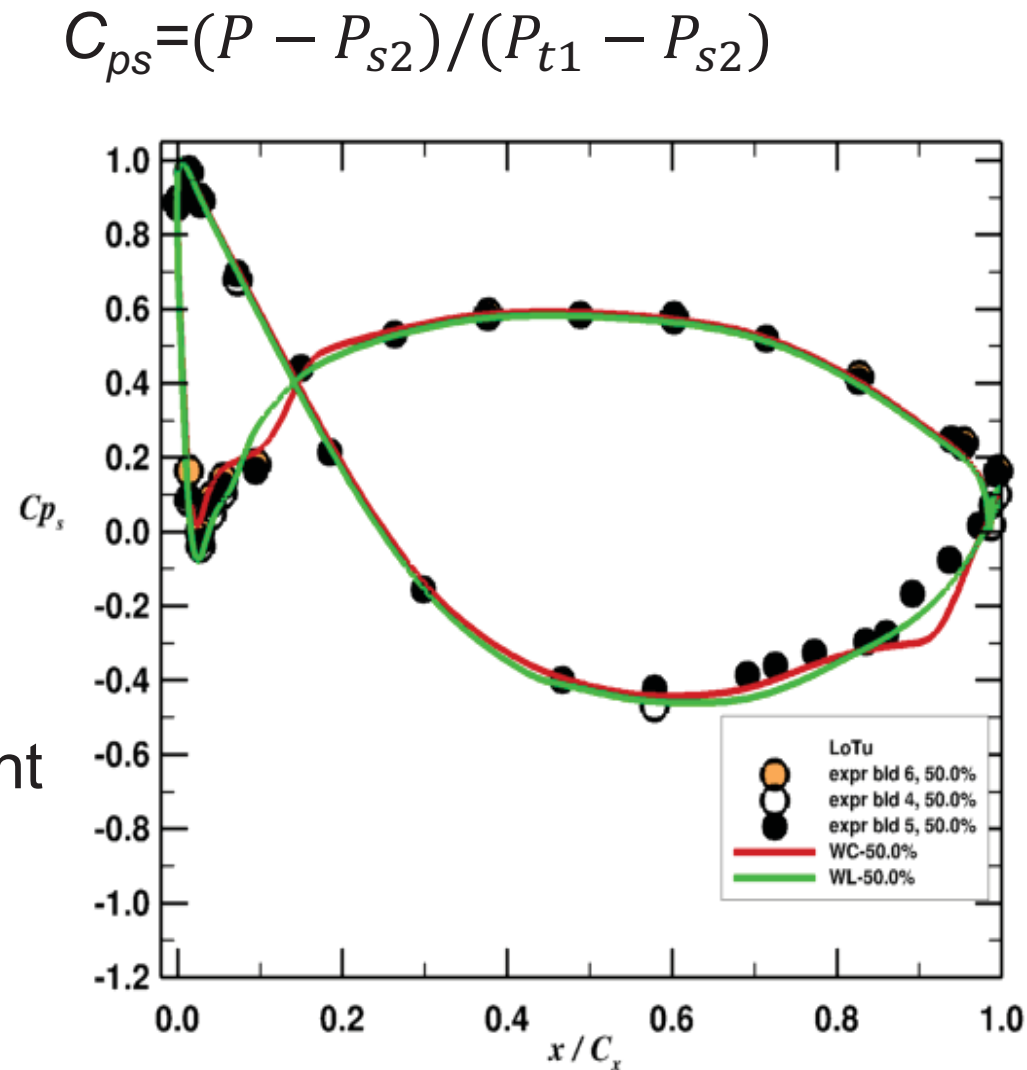


WC

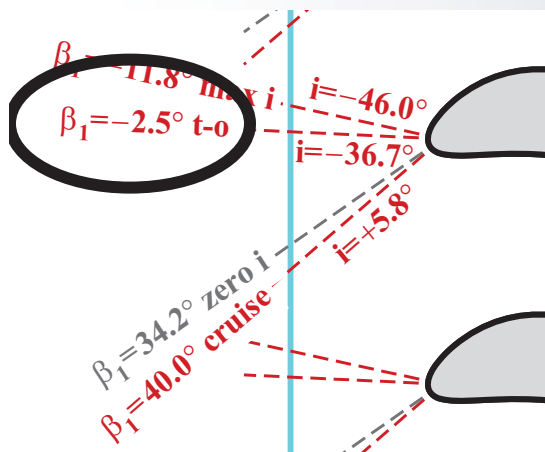
Pressure Distribution- Takeoff , Low Tu



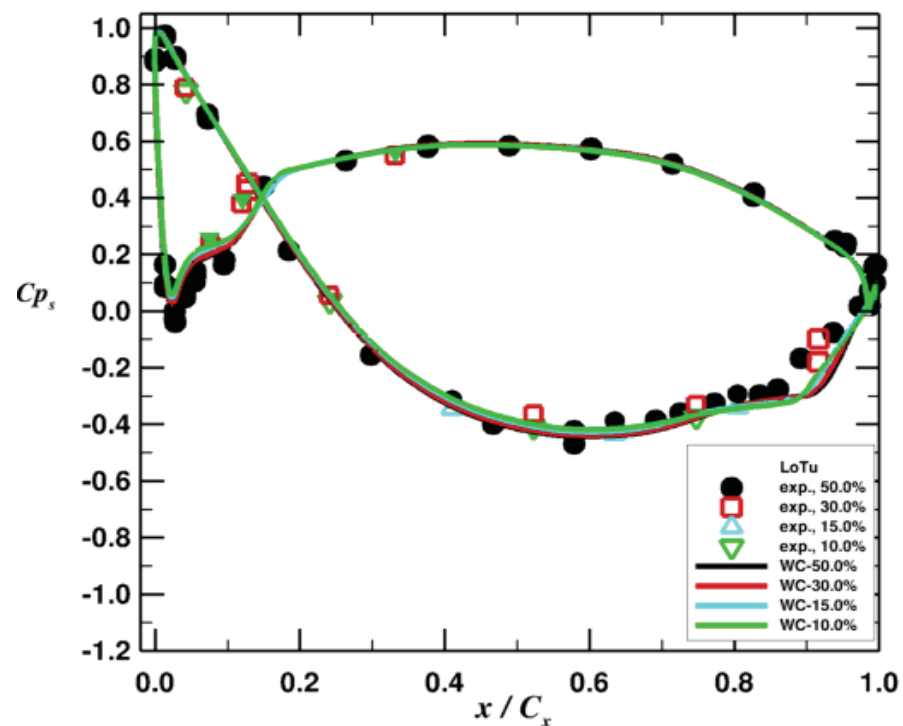
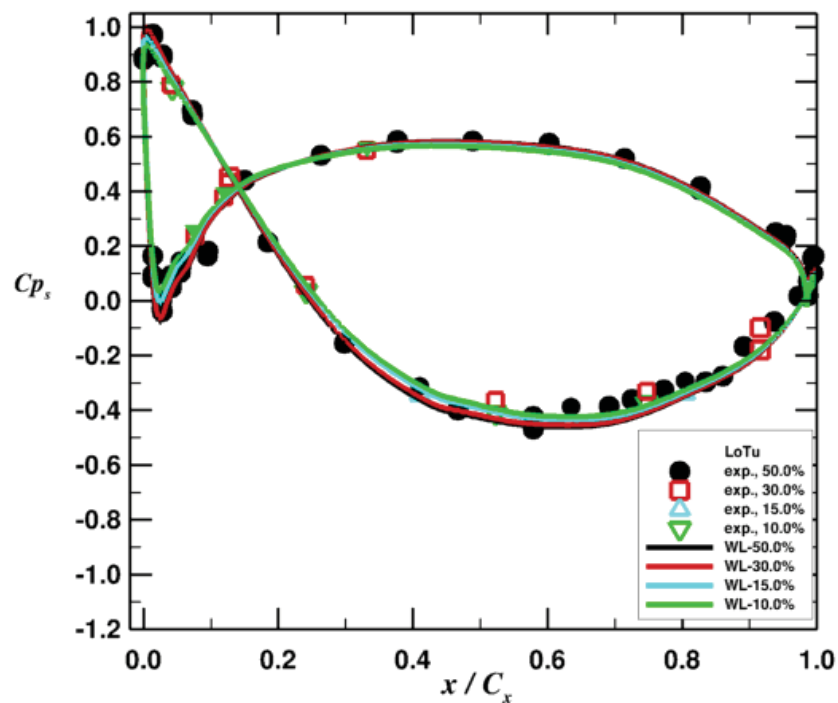
Mid-Span Static
Pressure Coefficient



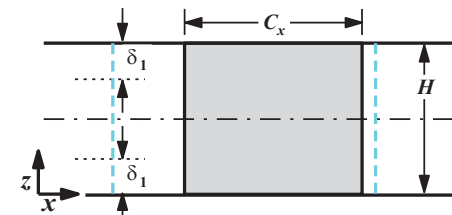
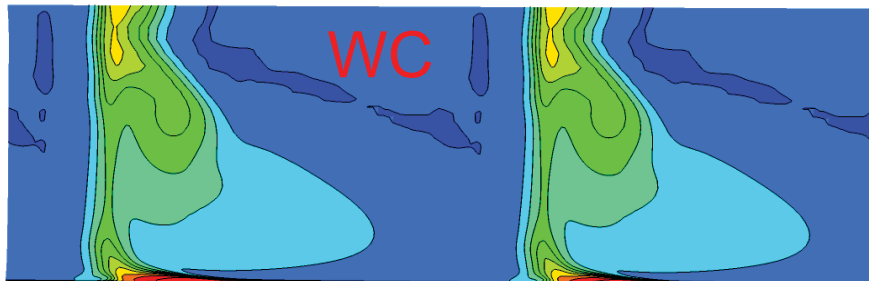
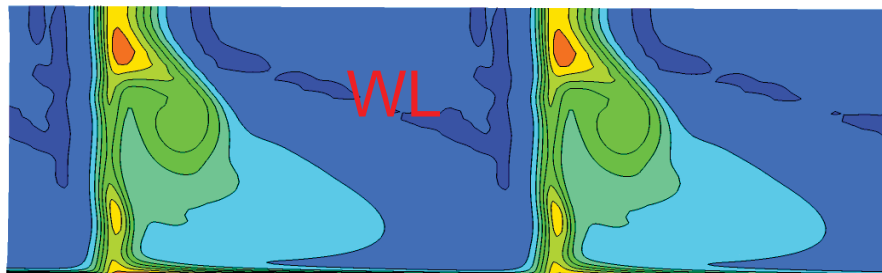
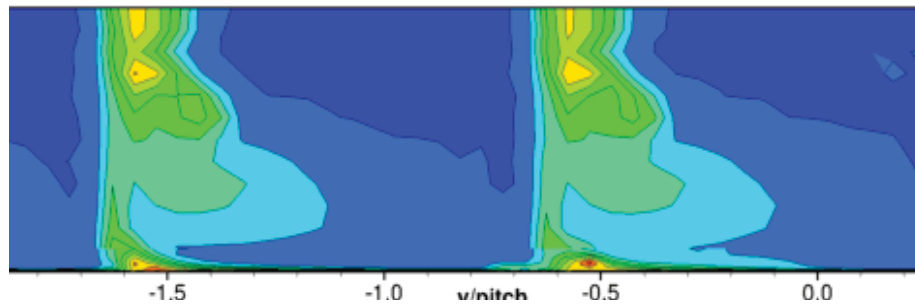
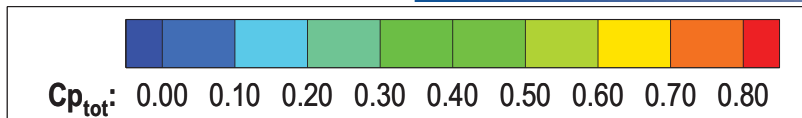
Pressure Distribution- Cruise, Low Tu



$$C_{ps} = (P - P_{s2}) / (P_{t1} - P_{s2})$$



C_{pt} for the Cruise incidence, Low Tu



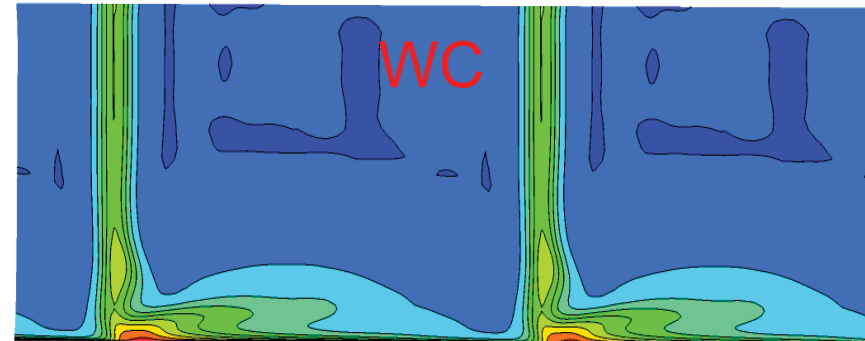
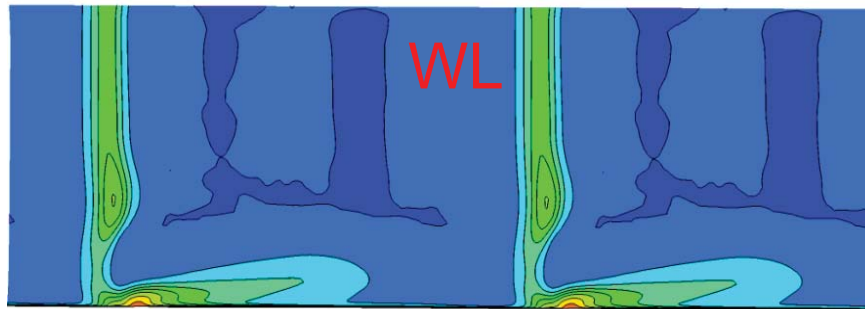
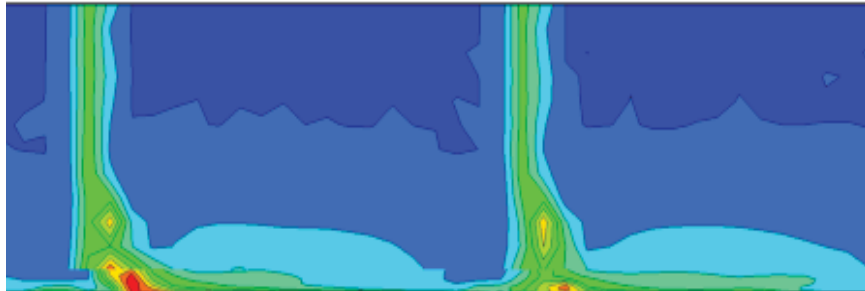
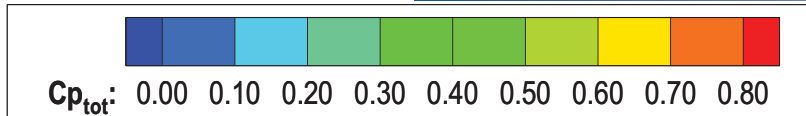
Probe Data 7% $x=1.07C_x$

CFD

$$C_{pt} = \frac{P_{t1} - P_{t-x}}{P_{t1} - P_{s2}}$$

- The wake total pressure loss coeff. measure C_{pt} over the half-span is well predicted.

C_{pt} for the Takeoff incidence, Low Tu



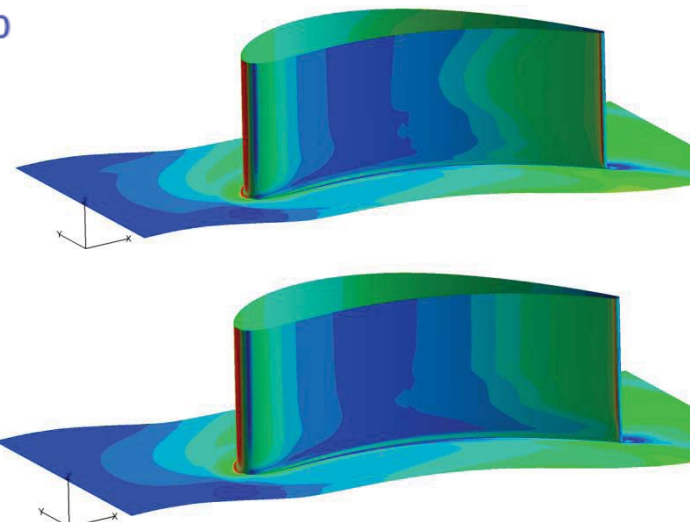
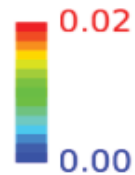
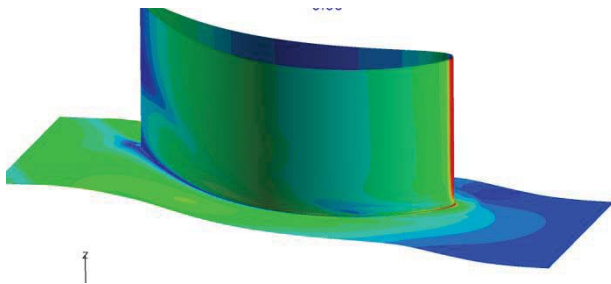
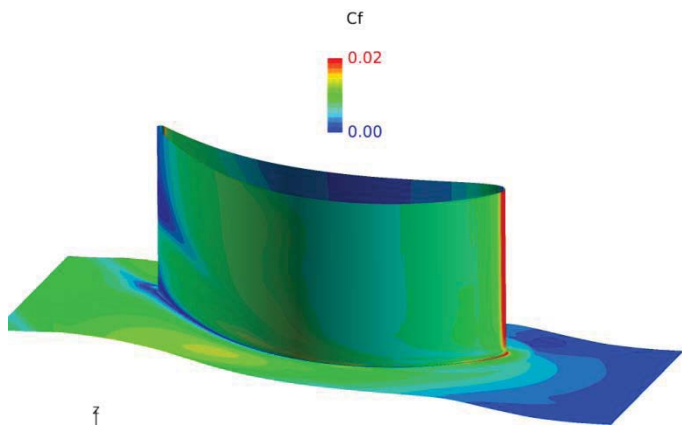
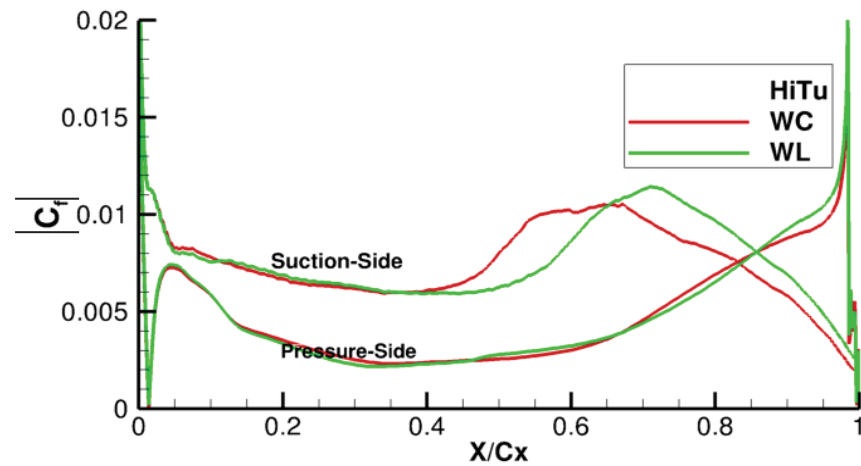
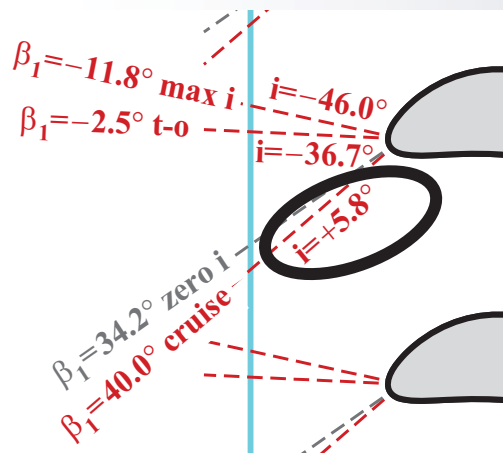
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Probe Data 7% $x=1.07CX$

CFD

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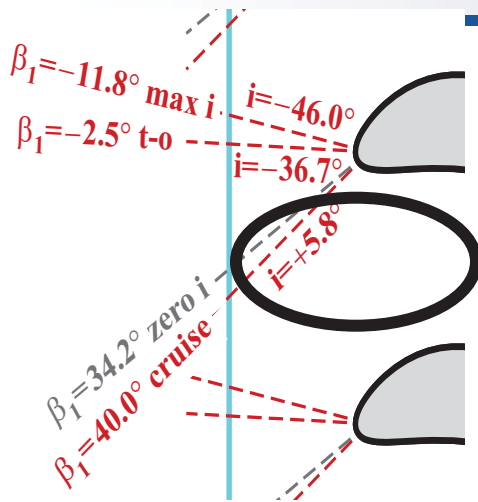
Transition, Cruise, High Tu



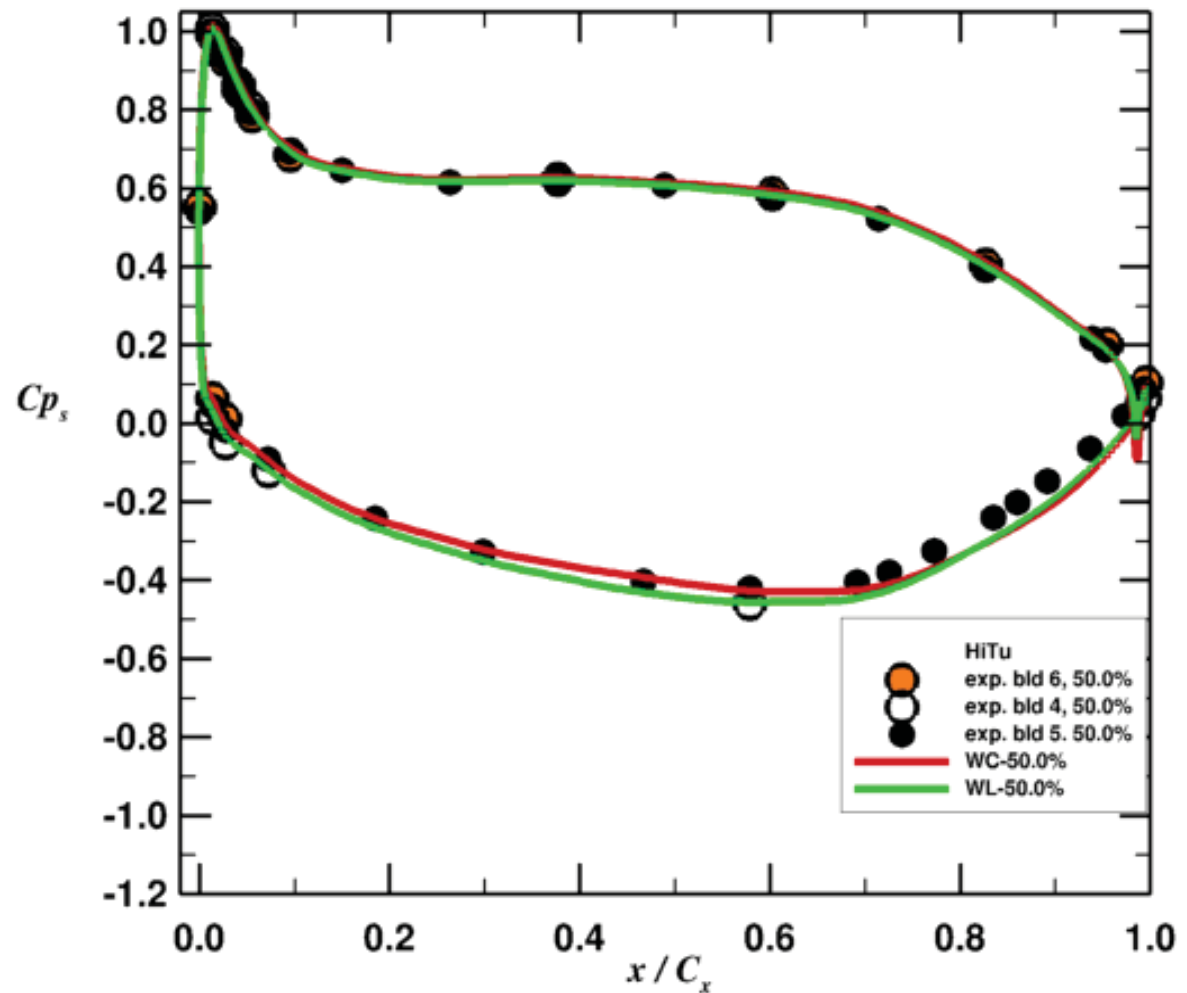
WL

WC

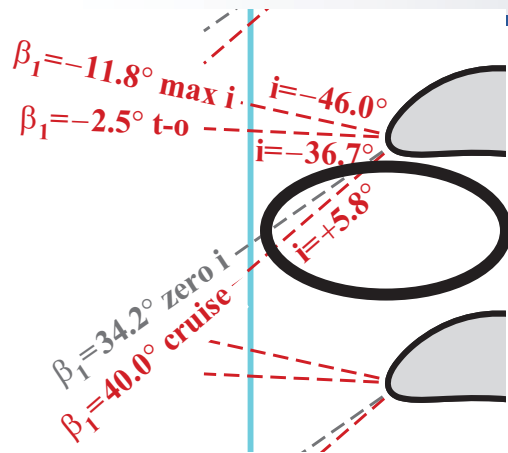
Pressure Distribution, Cruise, Hi Tu



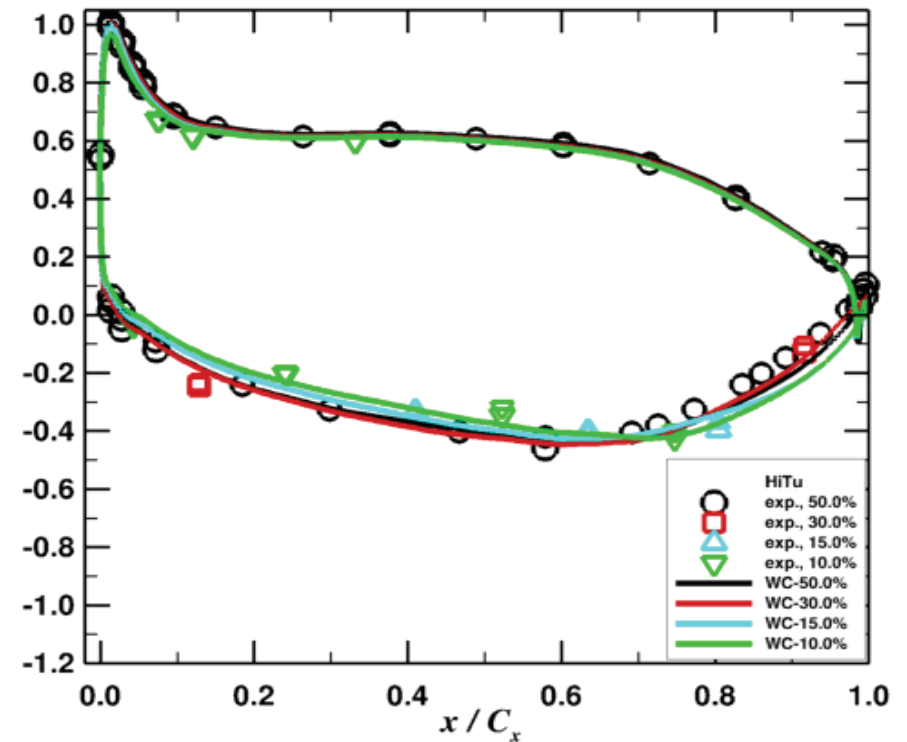
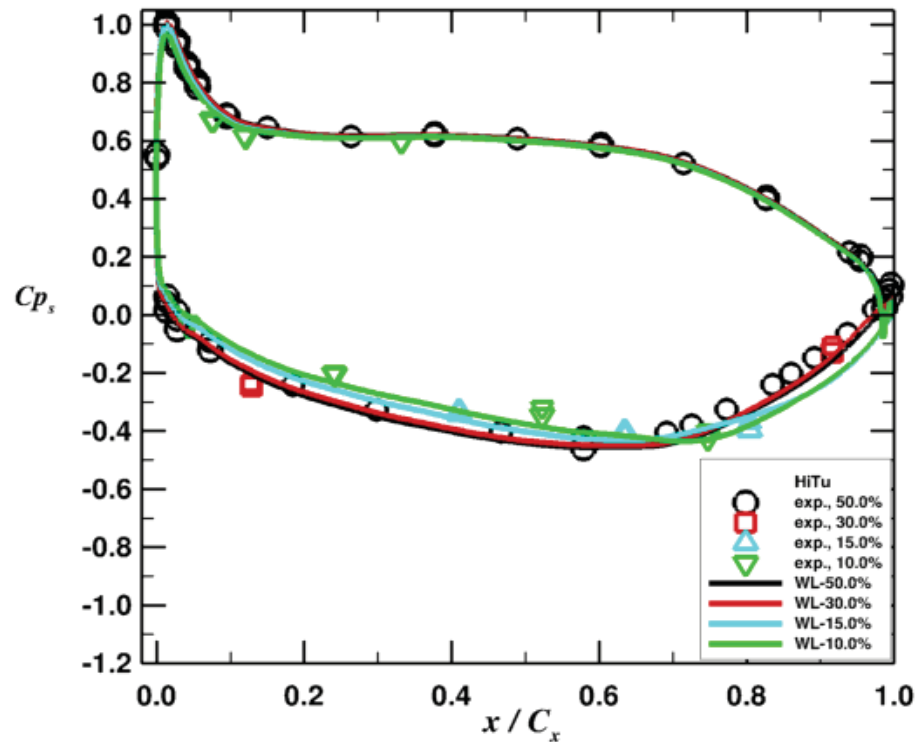
$$C_{ps} = (P - P_{s2}) / (P_{t1} - P_{s2})$$



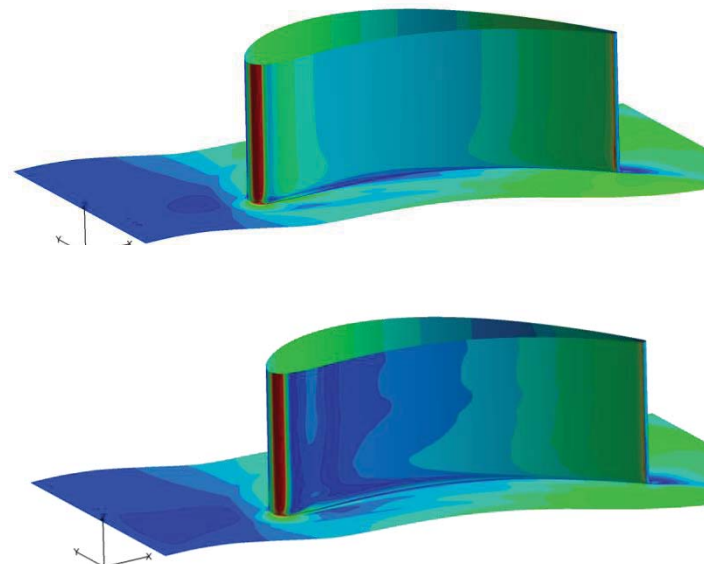
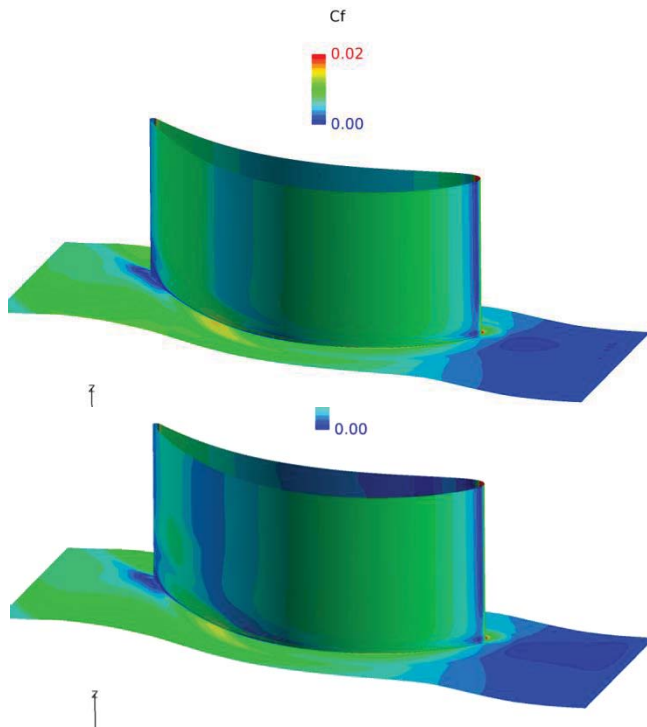
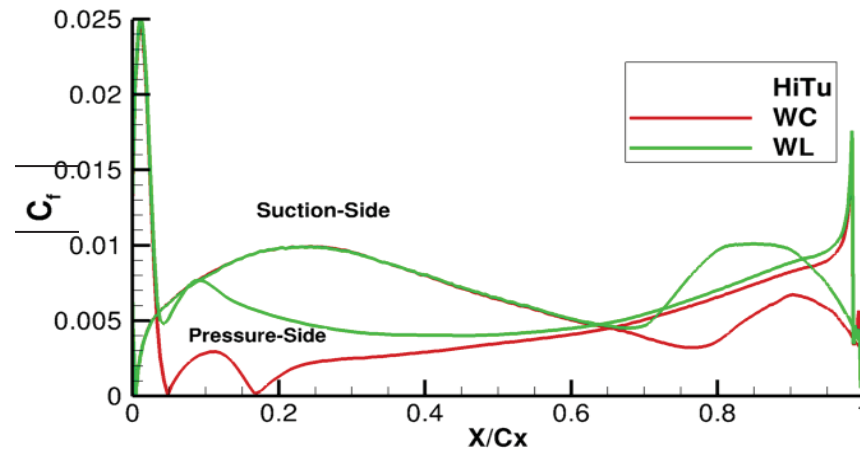
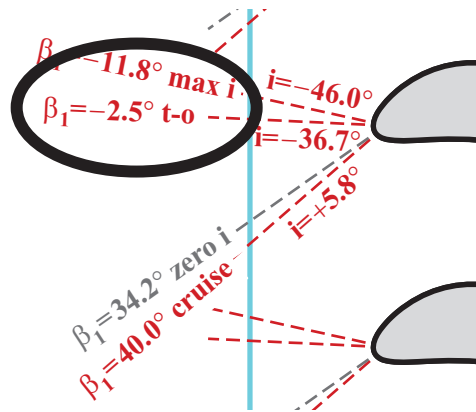
Pressure Distribution, Cruise, Hi-Tu



$$C_{ps} = (P - P_{s2}) / (P_{t1} - P_{s2})$$



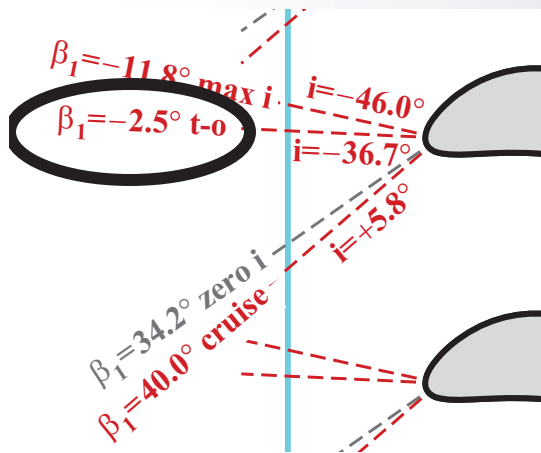
Transition, Takeoff, Hi Tu



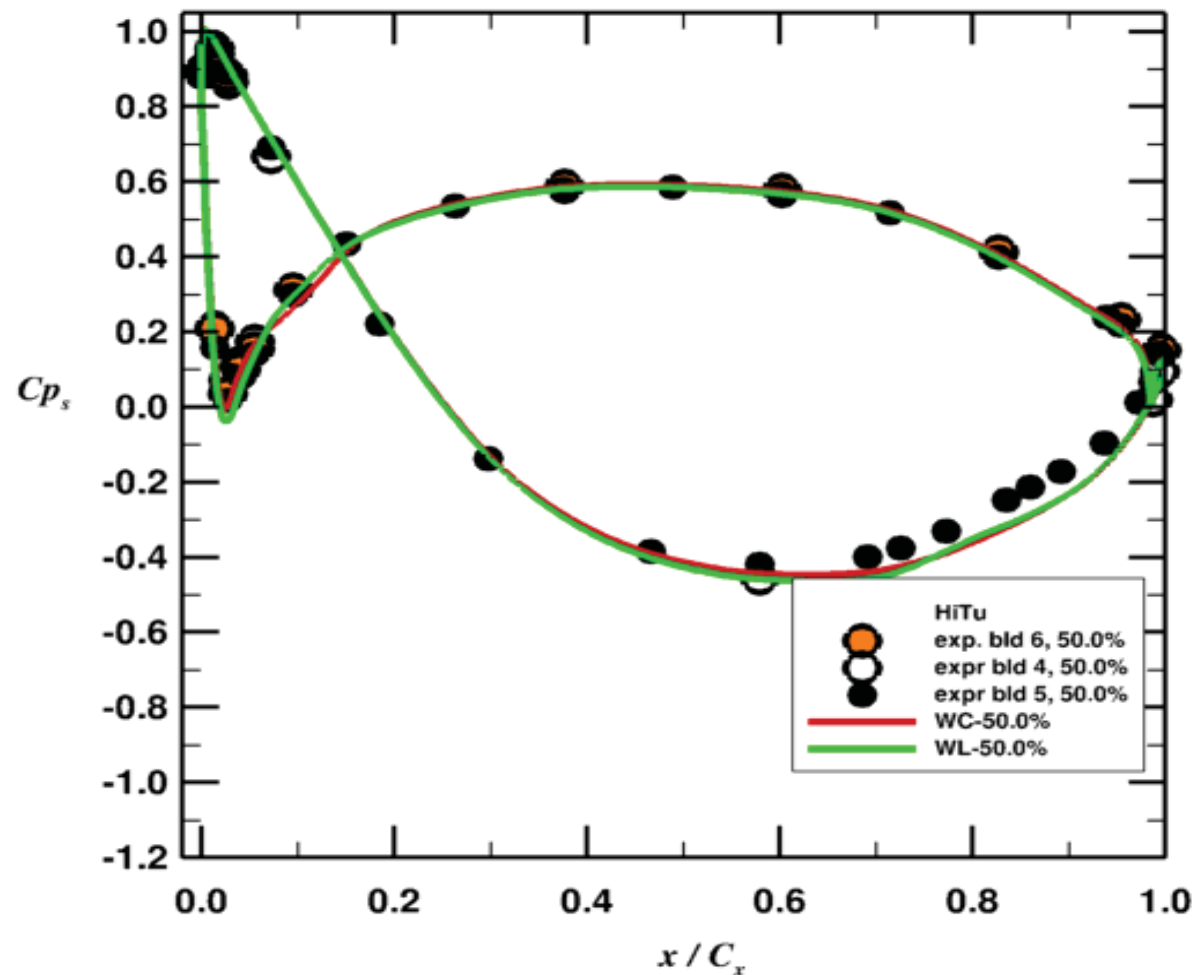
WL

WC

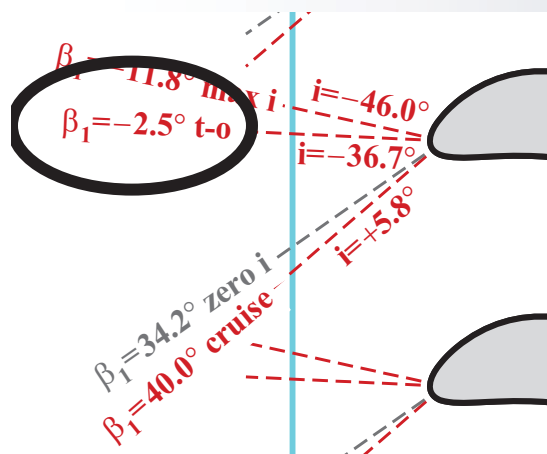
Pressure Distribution, Takeoff, High Tu



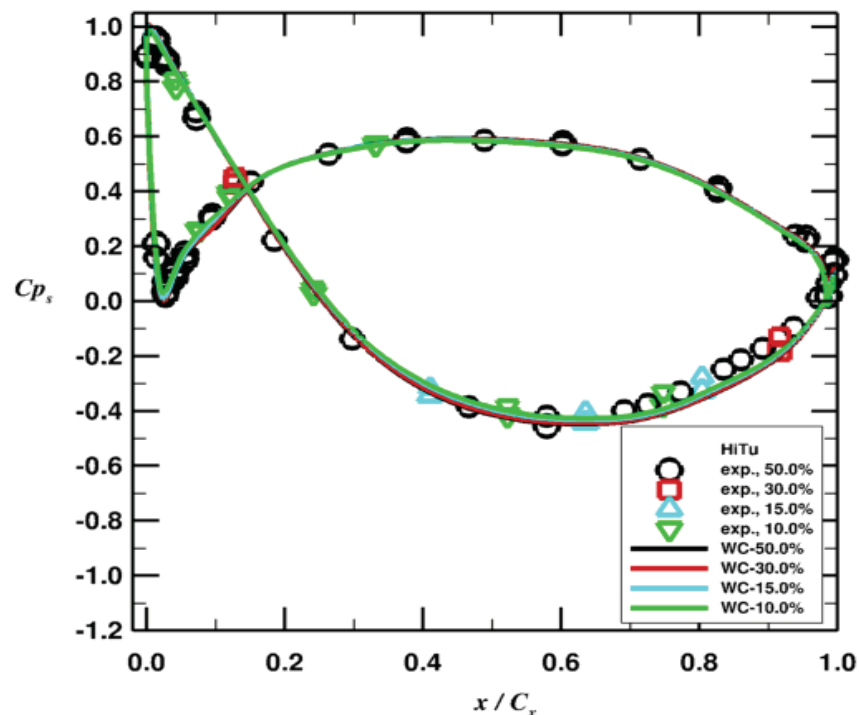
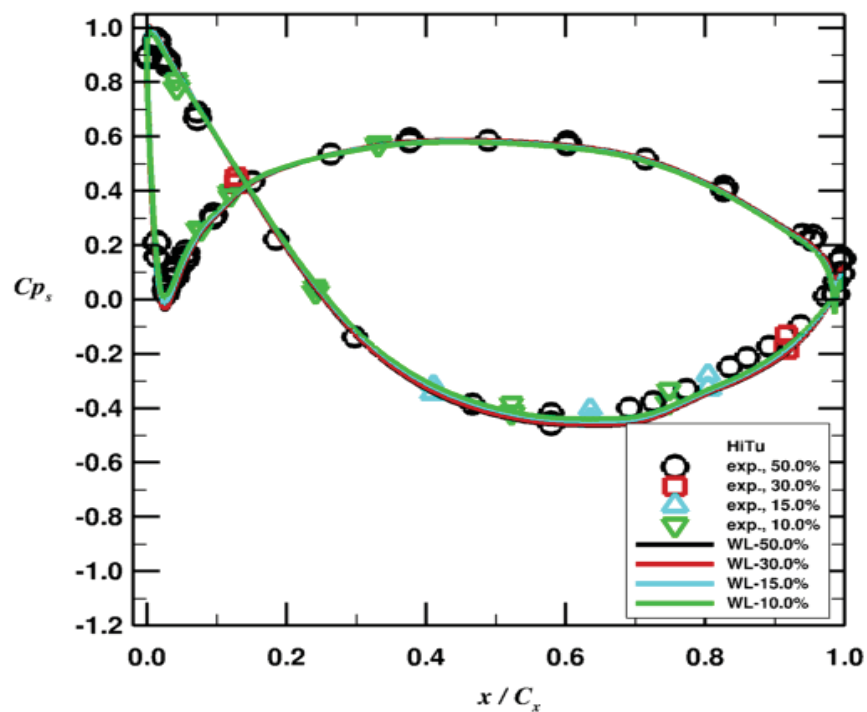
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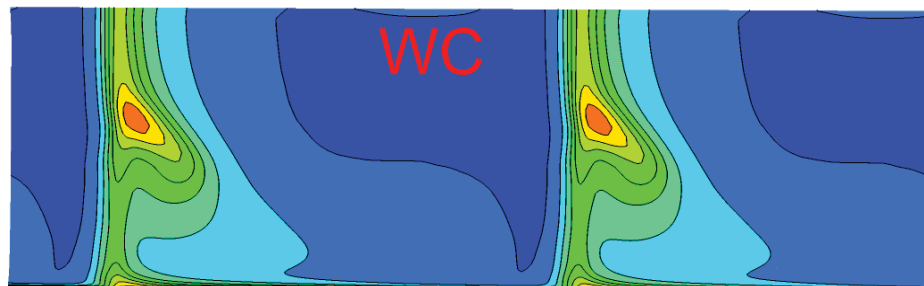
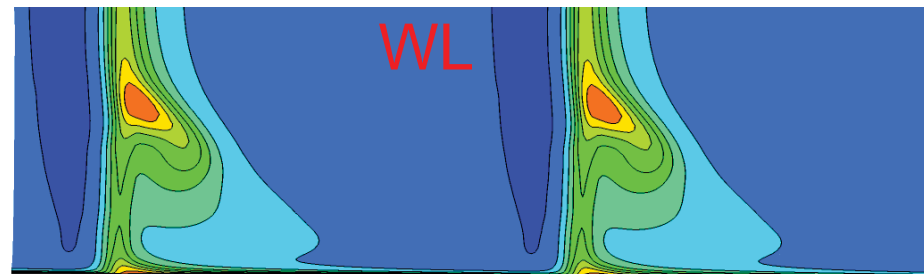
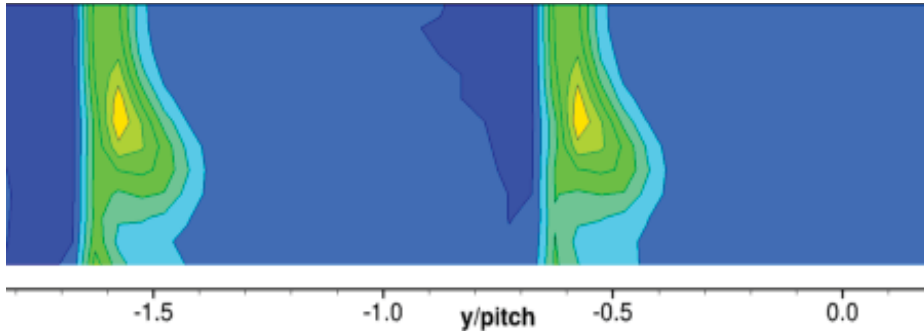
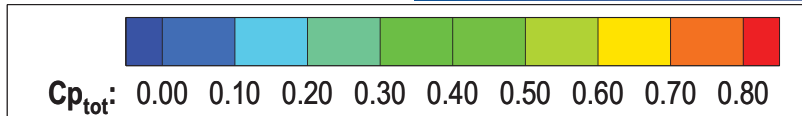
Pressure Distribution, Takeoff, High Tu



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C_{pt} for the Cruise incidence, High Tu



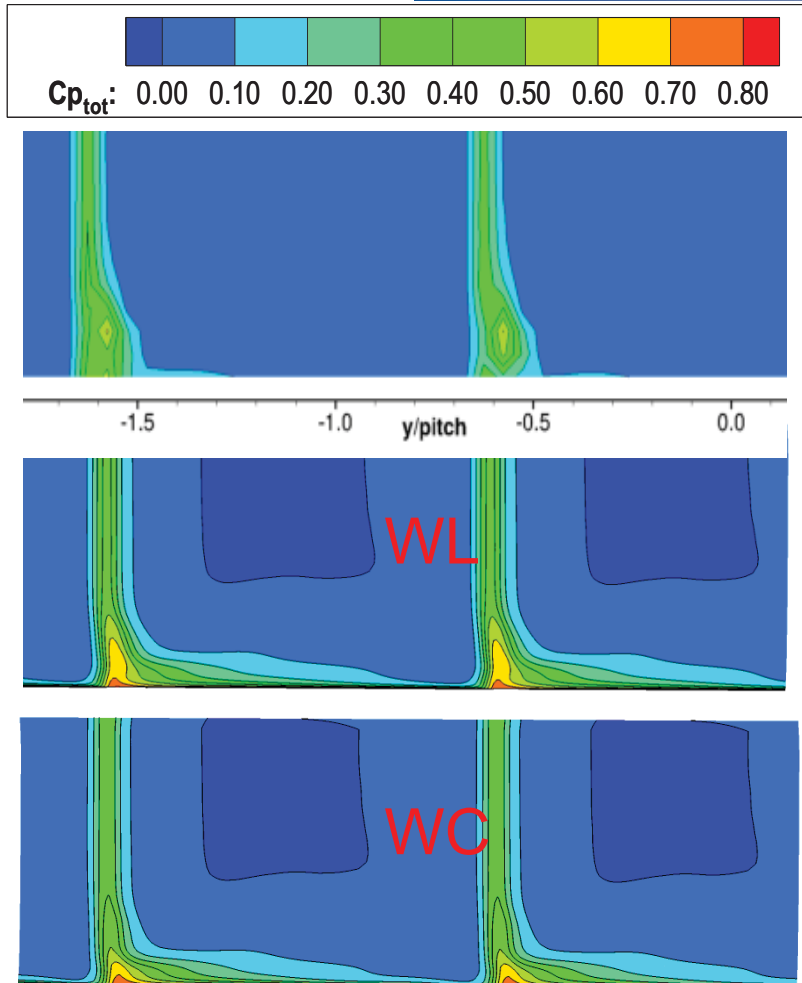
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Probe Data 7% $x=1.07CX$

CFD

- The wake total pressure loss coeff. measure C_{pt} over the half-span is conservative.

C_{pt} for the Takeoff incidence, High Tu



$$C_{pt} = \frac{P_{t1} - P_{t-x}}{P_{t1} - P_{s2}}$$

Probe Data 7% $x=1.07CX$

CFD

- The wake total pressure loss coeff. measure C_{pt} over the half-span is well predicted.

Summary and Conclusions

- For the VSPT, flow transition/separation has been identified as an important process.
- Large variations in incidence angles require models that can reasonably compute these flows.
- Numerical modeling and validation with companion experimental data of the 3-D flow in a 2-D transonic linear cascade at the two incidence angle conditions corresponding to **Takeoff** and **Cruise** were made.

Summary and Conclusions

- The inlet turbulent length scale, which determines the decay rate of turbulence, was determined from the data.
- At low Tu , WL model missed separation entirely due to early transition while WC model predicted a laminar boundary layer and the subsequent separation as described by the data.
- At higher Tu the two models performed similarly and results were quite satisfactory. At the takeoff condition WC model shows separation on the pressure side while WL model does not.
- Losses are generally better predicted with the WC model.